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Gradus, R.H.J.M.

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[...]VERSITY
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UNIVERSITEIT
BRABANT

POSTBOX 90153
5000 LE TILBURG
THE NETHERLANDS

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OPTIMAL DYNAMIC PROFIT TAXATION: THE DERIVATION OF FEEDBACK STACKELBERG EQUILIBRIA

Raymond Gradus

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OPTIMAL DYNAMIC PROFIT TAXATION: THE DERIVATION OF FEEDBACK STACKELBERG EQUILIBRIA

Raymond GRADUS

Tilburg University, P.O.Box 90153 5000 LE Tilburg, The Netherlands

ABSTRACT

In this paper we develop a framework for determining optimal profit taxation for a welfare-maximising government. We show that there is a dynamic trade-off between public consumption now and in the future. Two possible solutions are derived. The first solution, which is the formal outcome of an open-loop Stackelberg equilibrium of a game between government and firms, is time-inconsistent. The second solution, which corresponds to a feedback Stackelberg equilibrium, is time-consistent, but yields a lower value of steady-state utility. The outcome of the feedback Stackelberg equilibrium depends on the number of firms in this economy. If the number of firms is large this equilibrium coincides with the open-loop Nash solution. Furthermore, we show the dynamic paths if the economy goes from its feedback to its open-loop steady state.

1. INTRODUCTION

In this paper we focus on the problem of the trade-off between investment behaviour of the firm and the tax policy of a 'rational' government. The government may announce a relatively low corporate tax rate, resulting in a lower level of public consumption than preferred by consumers. But this relatively low tax rate also implies a higher level of investment, which generates a higher level of total consumption in the future. In this paper we model this dynamic trade-off between corporation taxation now and in the future within a macro-economic framework.

The question of optimal taxation is a very broad one and many strands of literature can be identified, see for example Ramsey (1927), Sandmo (1976), Atkinson and Stiglitz (1980), Laffer (1981). The first distinction can be made between papers, which deal with this problem in a static framework (e.g. Ramsey (1927) and Laffer (1981)) or in a dynamic way (e.g. Kydland and Prescott (1980), Turnovsky and Brock (1980)). In this paper we deal with the problem of optimal dynamic taxation. We can also distinguish between different kinds of tax rates, e.g. sales tax, wage or income tax and profit tax. In the literature most interest has been paid to the problem of optimal static income tax, because of its impact on the supply and demand for labour (e.g. Laffer (1981)). Relatively little interest has been paid to the optimal corporate taxation. An example can be found in Fischer (1980), in which a two period problem is treated. However, this paper disregards some important issues because there is no separation between the decision of the firm and the consumer and no taxation in the first period. We believe that profit taxation has a greater impact on the outcome of the economic process than the attention in the literature suggests, because of its impact on the capital accumulation and the investment decision. In this paper we therefore treat the problem of optimal profit taxation.

With respect to the behavioural assumptions we develop a game-theoretic framework. Firms and consumers take the decisions of the others as given, but the government takes into account the way in which the other agents will take their decisions. So, the solution corresponds to a Stackelberg game with the government as leader and the firms and the consumers playing Nash against each other (cf. Başar and Olsder (1982, chapter 7)). In this paper different solution concepts are analysed. The first solution concept is the open-loop Stackelberg equilibrium. In this case all players commit themselves to their announced strategies at the beginning of the planning period. However, this solution is time-inconsistent, i.e. becomes suboptimal over time and is only credible, if the firm has reasons to believe that the government will not deviate from its announced plan (e.g. Kydland and Prescott (1977), Calvo (1978)). So, even for an economy in which capital tax is the only tax, there can be time-inconsistency. Therefore, in this paper we want to treat the problem of dynamic inconsistency in case of only capital taxation more carefully.

If there is no commitment or reputational forces, this solution concept is no longer useful. In that case the feedback Stackelberg equilibrium can be used. However, in general such a feedback Stackelberg equilibrium is not easy to calculate. Until now only for a linear-quadratic game a general solution has been be given. This is the reason why most economic applications in the literature are of this type, see for example Miller and Salmon (1985), Başar, Turnovsky and d'Orey (1988). The aim of this paper is to give a feedback Stackelberg equilibrium for a game, which is not linear-quadratic. Furthermore, it will turn out that the outcome of this feedback Stackelberg equilibrium depends on the number of firms in the economy.

In the next section we describe the model for the firms, which is based on neo-classical theory (e.g. Lucas (1967)), while in the third section the model for the consumers is given. For reasons of analytical tractability we assume that there is only one type of consumer and one type of firm. In the fourth section the behaviour of the government is described for the case that the government commits itself to its announced strategy. In the fifth section the implications of the problem of time-inconsistency are given, while in the sixth section the feedback Stackelberg equilibria are calculated. Furthermore, we compare the open-loop and feedback solutions by applying a numerical example. In section 7 the evolution of the economy is given, if it moves from the time-consistent to the time-inconsistent steady-state. The last section concludes and gives some suggestions for future research.

2. THE FIRM'S DECISION PROBLEM

Consider a firm operating in an environment without exogenous uncertainty. The firm decides on its demand for labour and investment, which are conditional on its expectations, present and future profit tax rates, present and future interest rates. The firm maximises its discounted stream of net cash flows (cf. Van der Ploeg (1987))

$$\max_{i,l} \int_0^\infty [\{f(k(t),l(t))-wl(t)\}(1-\tau(t))-i(t)-\varphi(i(t))]e^{-\int_0^t r(v)dv}\,dt, \qquad (1)$$

where: k: the level of the capital stock,

l: the number of employed workers,

i: the rate of investment,

w: the real wage rate (=constant),

τ: the level of corporate tax rate,

r: the rate of interest,

f(k,l): production function,

$\varphi(i)$: internal adjustment costs,

$$\varphi(0)=0,\ \mathrm{sign}(\varphi')=\mathrm{sign}(i),\ \varphi''>0.$$

With respect to the production function we assume that capital and labour are substitutes and production is characterised by constant returns to scale (so that $f_{ll}f_{kk} - f_{kl}^2 = 0$). The planning horizon is infinite. The strictly convex function $\varphi(.)$ captures that internal adjustment costs increase and are zero only if gross investment is zero. It ensures that capital adjusts in a sluggish manner to changes in interest rate and corporate tax rate. The firm will maximise (1) subject to the capital accumulation equation

$$\dot{k}(t) = i(t) - \delta k(t), \tag{2}$$

where: δ: rate of depreciation.

The necessary conditions for the firm's optimal control problem are:[1]

$$\dot{q}(t) = (r(t)+\delta)q(t) - f_k(1-\tau(t)),\quad \lim_{s\to\infty} e^{-\int_t^s r(v)dv} q(s)k(s) = 0, \tag{3}$$

$$\varphi'(i(t)) = q(t) - 1, \tag{4}$$

$$f_l = w, \tag{5}$$

$$\dot{k}(t) = i(t) - \delta k(t), \tag{6}$$

in which: q: the (undiscounted) shadow price of capital.

If we assume that $f(k,l)$ is a Cobb-Douglas production function[2] and that wages are constant, then labour is a linear function of capital and the

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1) To be precise, we have to distinguish between open-loop and feedback information structure for the firm. However, if we will see in appendix 2 and 3 for an economy with many firms this makes no difference.

2) To obtain analytical results we specify the production function as a Cobb-Douglas function. However, we think the whole derivation also holds for other production functions.

partial derivative with respect to capital is a constant. So (3)-(6) can be rewritten as follows (dropping time-arguments):

$$\dot{q} = (r+\delta)q - a(1-\tau), \tag{7}$$
$$i = \Phi(q),\ \Phi'>0,\ \Phi(1)=0, \tag{8}$$
$$l = hk, \tag{9}$$
$$\dot{k} = i - \delta k, \tag{10}$$

where a and h are positive constants.

With respect to fixed wages we can assume that there is some union power, that ensures wages to be equal to some fixed level w (e.g. Oswald (1985)). It is also possible to model a labour market, where w is determined by supply and demand for labour (e.g. Abel and Blanchard (1983)). In that case there may be full employment.

The steady-state investment level is just sufficient to provide for replacement investment, $i^{*}=\delta k^{*}$, so that the shadow price of capital exceeds one, $q^{*}=1+\varphi'(\delta k^{*})$. This means, that the shadow price of a unit of capital equals the costs of purchasing investment goods plus the marginal costs of adjusting the capital stock. The steady-state capital follows from (7)-(10) and can be expressed as

$$k^{*} = \frac{1}{\delta}\cdot\Phi\left(\frac{a(1-\tau^{*})}{r+\delta}\right),\ k^{*}_{\tau}<0,\ k^{*}_{r}<0. \tag{11}$$

So if the corporate tax rate raises, capital formation decreases and there will be less employment.

3. THE CONSUMER'S DECISION PROBLEM

In this section we model the saving-investment decision, similar to Abel and Blanchard (1983) or Van de Klundert and Peters (1986) for example. The consumer can choose between consumption now or in the future given his income from labour, dividend and interest. In this way consumption is an increasing function of total wealth in the spirit of Metzler (1951) and an equilibrium between aggregate demand and supply is achieved by the endogenous adjustment of the sequence of current and future interest rates. We assume that the consumer takes the decision of the firm and the government as given. Furthermore, the consumer maximises a concave utility function, which depends on private and public consumption.

The consumer chooses a path of consumption, which maximises the present value of utility over time

$$\max_{c} \int_{0}^{\infty} u(c,g)e^{-\beta t}\,dt. \tag{12}$$

where: β: social discount rate (=constant),
c: private consumption,
g: public consumption.

The wealth constraint can be expressed as

$$\dot{b} = rb + \pi + wl - c, \tag{13}$$

where: b: amount of bonds hold by consumer,
π: dividends.

So income is the sum of wages, interest on savings and dividends. The current-value Hamiltonian for this problem is

$$H = u(c,g) + x(rb + wl + \pi - c). \tag{14}$$

The optimality conditions are:

$$u_c = x, \tag{15}$$

$$\dot{x} = (\beta-r)x, \lim_{t\to\infty} e^{-\beta t}b(t) = 0, \tag{16}$$

in which: x: the costate variable associated with the dynamic budget constraint.

To exclude paths from borrowing forever we assume that there are No-Ponzi-Games

$$\lim_{t\to\infty} e^{-\int_0^t r(v)dv} b(t) = 0. \tag{17}$$

In section 2 we did not say anything about the way the firms finance their investment. After paying wages to the worker, the firm has to decide how to distribute profit and finance investment. It may finance investment by retained earnings or issuing new shares or bonds. For example, we can assume that replacement investment is financed out of retained earnings and that net investment is financed by bonds. However, because of the fact that the interest rate on bonds is also r and the Modigliani-Miller theorem holds, all financing schemes are equivalent in the sense that they lead to the same path of total consumption and investment; they differ, however, in terms of institutional arrangements (for a proof of this see Abel and Blanchard (1983, pp. 680-681)).

4. OPEN-LOOP STACKELBERG EQUILIBRIA

We assume that the government has the same utility function as the consumer (cf. Turnovsky and Brock (1980)), that public consumption will be financed from profit taxation and that there is no debt. As already noted in section 1, an important difference between government and firm or consumer is that the government takes account of the manner in which the firm and consumer react on its taxation decisions, while the firm and the consumer take the taxation decision as given. So the formal outcome of the game corresponds to a three person Stackelberg game with the government as leader and firm and consumer playing Nash against each other.

The government's problem for the case of open-loop information structures can be formulated as the following control problem:

$$\max_{\tau} \int_0^\infty u(c,g)e^{-\beta t} dt , \tag{18}$$

$$\text{s.t.: } \dot{q} = (r+\delta)q - a\{1-\tau\} \tag{19}$$

$$\dot{k} = \Phi(q) - \delta k, \tag{20}$$

$$c = \{1-\tau\}[f(k,l)-wl]-i-\varphi(i)+wl, \tag{21}$$

$$g = \tau[f(k,l)-wl], \tag{22}$$

$$u_c = x, \tag{23}$$

$$\dot{x} = (\beta-r)x, \tag{24}$$

$$\dot{b} = rb + \pi + wl - c. \tag{25}$$

Note that equation (21) represents the equilibrium on the goods market and that equation (22) represents the fact, that there is no debt, because at every time-point government's spendings, i.e. g, are equal to the revenues from taxation. Furthermore, we assume that there are Cobb-Douglas preferences and we have to remember that labour is a linear function of capital:

$$u(c,g) = \alpha \ln c + (1-\alpha)\ln g, \; 0<\alpha<1, \tag{26}$$

$$c = \{1-\tau\}ak + whk - \Phi(q) - \varphi(\Phi(q)), \tag{27}$$

$$g = \tau ak. \tag{28}$$

It should be noted that we can eliminate b and x. Substituting from (21) into (23) gives us a value for x. As already stated the stream of consumption will not be influenced by financial streams.

The maximisation of (18) with respect to (19)-(25) yields, by assuming an interior solution, the following necessary conditions:

$$\frac{\alpha}{c}\cdot\frac{\partial c}{\partial \tau} + \frac{1-\alpha}{g}\cdot\frac{\partial g}{\partial \tau} + \nu a = 0, \tag{29}$$

$$\dot{\nu} = \beta\nu - (r+\delta)\nu - \lambda\Phi'(q) + \frac{\alpha q \Phi'(q)}{c}, \; \nu(0)=0, \tag{30}$$

$$\dot{\lambda} = (\beta+\delta)\lambda - \alpha[(1-\tau)a+wh]/c - (1-\alpha)/k, \; \lim_{t\to\infty} e^{-\beta t}\lambda(t)k(t) = 0, \tag{31}$$

where: λ: the government's undiscounted marginal value of capital stock,

ν: the government's undiscounted marginal value of the shadow price of the capital stock to the firm (=q).

The Hamiltonian is defined by

$$H = \alpha\ln[\{1-\tau\}ak+whk-\Phi(q)-\varphi(\Phi(q))] + (1-\alpha)\ln(\tau ak) + \lambda(\Phi(q)-\delta k) + \nu((r+\delta)q-a(1-\tau)). \tag{32}$$

Together with the condition for the equilibrium in the goods market

$$f(k,l) = c + g + i + \varphi(i) \tag{33}$$

we have a complete macro-economic model, which is repeated in appendix 1. The model has 13 equations and 13 unknown variables and can be solved by the method of multiple shooting as explained in Lipton et al. (1982). Note that the condition for the equilibrium in the goods market, together with the anticipation that this condition will hold at future times, determines at any instant the complete term structure of interest rates. In the steady-state the rate of interest equals the social discount rate and personal savings are zero.

From equations (27), (28) and (29) we can derive:

$$\tau = T(k,\nu,q),\ T_k>0,\ T_q<0,\ T_\nu>0. \tag{34}$$

It should be noted, that the optimal tax rate will be chosen in such a way, that the following equation holds, along the equilibrium path (cf. (29)):

$$\frac{g}{c} = \frac{1-\alpha}{\alpha}\left(1 + \frac{\nu g}{(1-\alpha)k}\right). \tag{35}$$

The steady-state follows from eqs. (30) and (31) and can be expressed as:

$$\nu^* = -\frac{\lambda^*\Phi'(q^*)-(\alpha/c^*)\{q^*\Phi'(q^*)\}}{\delta} < 0^3, \tag{36}$$

$$\lambda^* = \{\alpha[(1-\tau^*)a+wh]/c^* + (1-\alpha)/k^*\}/(\beta+\delta) > 0. \tag{37}$$

So in the steady-state the amount of public consumption in total consumption is less than 1-α (cf. (35), (36)). Due to equations (12), (27), (36) and (37), the optimal tax rate in the steady-state can be derived:

$$\tau = T(k^*,\nu^*,q^*). \tag{38}$$

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3) assuming that $\lambda\Phi'-(\alpha/c)\{q\Phi'\}>0$, which is quite reasonable.

Equation (29) or (35) effectively says that the marginal utility from public consumption is less than the marginal utility from private consumption. This is contrary to the Fischer paper (1980) where marginal utility from private consumption equals marginal utility from public consumption.

5. ON TIME-INCONSISTENCY

In the previous section we have described an optimal profit taxation plan for the government. However, this optimal plan is time-inconsistent, because there is an incentive for the government to reoptimise and reconsider its tax strategy at some later date. Once the capital is installed, the government has an incentive to renege on its announcement and ask a higher tax rate. So, contrary to Fischer (1980) also in an economy with only one tax instrument there can be time-inconsistency. Note, that the marginal value to the government of the firm's shadow price must equal zero at the start of the planning period, because the firm's shadow price is free to jump at that point of time and therefore becomes effectively an additional policy instrument for the government. So, if the government has the possibility at some later point of time to make a new initial plan, this shadow price becomes zero again. The shadow price ν can be interpreted as a price of time-inconsistency. At a moment that almost all capital is installed, there is an incentive for the government to ask a higher tax rate, such that marginal utility from private consumption equals marginal utility from public consumption, i.e. $\frac{g}{c} = \frac{1-\alpha}{\alpha}$. The extra gain of increasing the tax rate, such that q decreases by 1, is equal to -ν. Hence, -ν equals the marginal value of cheating the firm by suddingly raising the tax rate. In this way -ν can be interpreted as the government's cost for sticking to its announced plan.

So if the firm has no reason to believe that the government will stick to its initial plan, the concept used in the previous section, which corresponds to an open-loop equilibrium of a Stackelberg game, is no longer a useful concept.

In the literature three main streams can be qualified for solving the problem of time-inconsistency. The first attempt is what is called the loss of leadership (cf. Buiter (1983)). In this view the government gives up its role as leader and the interactions between private sector and government is viewed as a Nash rather than a Stackelberg dynamic game. The acceptance of this view would, however, mean the denial of existence of policies which have announcement effects. Secondly, memory strategies, threats and incentives can be used to substain the time-inconsistent solution (cf. Backus and Driffill (1985), Barro and Gordon (1983)). Thirdly, we can use recursive or so-called feedback methods. The present government's leadership is preserved with respect to the private sector, but it is lost with respect to future governments, which are free to optimise.

The aim of this paper is to use the third approach to solve the time-inconsistency problem. For the model given in the previous sections we derive the feedback Stackelberg solution in the next section.

6. FEEDBACK STACKELBERG EQUILIBRIA

In general it is not easy to derive the feedback Stackelberg equilibria for a non-linear quadratic continuous time game. Some examples can be found in the literature (e.g., Başar, Haurie, Ricci (1985), Van der Ploeg and De Zeeuw (1989)). In the appendices 2 and 3 the derivation is given for the model presented in section 2, 3 and 4. It is shown that the outcome depends on the number of firms in the economy. Therefore, we distinguish between two cases. In the first case there are many identical firms and all firms are very small. In the second case there is only one firm.

If there are many firms we are able to prove that the open-loop Nash equilibrium is a candidate for the feedback Nash and Stackelberg equilibrium, where the Nash equilibrium effectively sets $\nu(t)=0$ for $t \geq 0$ and ignores (19). The reason for this is that the firm is so small that the information about the way that the tax rate depends on the capital stock yields no advantage, because it can not influence it. The Nash equilibrium is time-consistent, because $\nu(t)=0$ for $t \geq 0$ implies time-consistency (cf. Pohjola (1986)). The open-loop Nash solution is easy to calculate and it turns out that the optimal tax rate is given by

$$\tau = T(k,0,q), \; T_k>0, \; T_q<0. \tag{39}$$

Along the equilibrium path the following equation holds: $\frac{g}{c} = \frac{1-\alpha}{\alpha}$. So, given a certain level of capital, the tax rate in the feedback Stackelberg equilibrium is higher than in the open-loop Stackelberg equilibrium. Because there is open-loop information structure the behaviour of the firms and consumers are the same as in section 2 and 3. From equations (7)-(10) it follows that the marginal productivity and the shadow price of capital, i.e. q^*, is lower in the feedback Stackelberg solution. Hence, less capital is accumulated and unemployment is higher. In this regime there is a reduction in the government's utility and a reduction in the stream of the firm's cash-flow compared with the open-loop Stackelberg solution (see table 1).

If there is only one firm the open-loop Nash equilibrium is no longer a candidate for the feedback Stackelberg equilibrium. The difference between both concepts lies in the behaviour of the firm and not in the behaviour of the government. The government's tax rate still can be obtained from equation (39) and it still holds that $\frac{g}{c} = \frac{1-\alpha}{\alpha}$. The firm's equation (7) changes into

$$\dot{q} = (r+\delta)q - a(1-\tau) + \frac{(1-\alpha)(i+\varphi(i))}{k}. \tag{40}$$

Hence, in this economy there is less investment and capital than in an economy with many firms, because of the fact that the firm takes into account the negative effects of its capital accumulation on taxation (cf. (39)).

[insert table 1]

So for both players it is better that open-loop is played (see table 1), but at the moment that the capital stock is built up, there is an incentive for the government to reoptimise and ask a higher tax rate. The firm's outcome is, of course, lower, if the government cheats the firm by suddenly asking the high rate instead of sticking to its announced plan. Therefore, a time-inconsistent plan requires binding commitments to force the government to stick to its announced tax strategy.

The nature of the solutions examined may be further clarified by a numerical example, which is based on the following two assumptions:

(i) quadratic adjustment costs:

$$\varphi(i)=\eta i^{2}, \tag{41}$$

(ii) CD-production function:

$$f(k,l)=k^{\sigma}l^{1-\sigma},\ 0<\sigma<1, \tag{42}$$

and the following parameter values: $w=0.5$, $\sigma=0.375$, $\eta=4.0$, $\delta=0.05$, $\beta=0.03$ and $\alpha=0.8$. In table 2 the steady-state values for the different solution concepts are given.

[insert table 2]

This example makes clear the difference between the open-loop and the feedback solution. The feedback solution yields a higher value of steady-state tax rate and a lower level of capital stock than the open-loop solution (see table 2). This lower level of capital stock in the feedback case yields a lower level of steady-state utility. In the open-loop case the share of public consumption goods in total output is lower, but private consumption and total utility will be higher because there is more capital. Moreover, the loss in welfare increases if the number of firms is small in this economy.

7. THE DYNAMIC EVOLUTION OF THE ECONOMY

In sections 5 and 6 we have described the steady-states for the feedback and open-loop Stackelberg equilibria. In this section we describe the paths of the economic variables, when the economy goes from its feedback (for many firms) to the open-loop equilibrium. Because of adjustment costs the economy moves slowly to its new steady-state. To obtain the solutions we use a multiple-shooting for rational expectations models developed by Lipton et al. (1982). As a matter of fact the system described in appendix

1 is called a two-point boundary problem with 3 backward-looking (k, b and ν) and 3 forward-looking variables (q, x and λ).[4] This path from the open-loop to the feedback steady-state can be interpreted as an economy where the government builds up credibility.[5]

[insert table 3]

In table 3 we see that the economy slowly adjusts to its new steady-state. At time-point 0 the level of government's and consumers' consumption is lower and the level of investment has increased by more than 31%. Furthermore, the government reduces the level of profit taxation. One could raise the question why the government does not lower immediately its tax rate to the new steady-state. However, the government needs some time to build up credibility. We see that the tax rate is at its lowest level after 10 periods, because the government wants to stimulate capital accumulation. At time-point 10 also the level of government's consumption is at its lowest point. However, at time-point 100 we see that the level of government's consumption is above the level of the initial steady-state. Although the share of public consumption in total output is less, the amount will be larger. This example clearly points out the importance of government's credibility.

Also the interest rate will have a jump at time-point 0. It should be noted that the interest rate clears the good market. At time-point 0 there is a growing interest in investment and the interest rate goes up. Because of the fact that the capital stock increases, the interest rate decreases smoothly to its steady-state value.

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4) This system satisfies the saddle point property of a perfect-foresight system, since there are three stable and three unstable eigenvalues (cf., Buiter (1984)).

5) To get a faster move from its old to its new steady-state we changed the following parameter values of table 2: w=1.0 and η=4.0. So, the steady-state values are different from table 2.

8. CONCLUSIONS

In this paper we have developed a macro-economic dynamic model with value-maximising firms, infinitely long-lived utility-optimising consumers and a government, which tries to choose its profit tax in such a direction that the utility of the consumer is maximised. The formal structure of the interaction between government and firms or consumers corresponds to a Stackelberg game with the government as leader. However, the introduction of an optimising government in our framework induces that in a open-loop game its announced optimal plan is intertemporally time-inconsistent. So, if there is no reason to believe that the government will stick to its announced plan, this open-loop concept is no longer useful. In that case the solution can correspond to the equilibrium of a feedback Stackelberg game, which is by definition time-consistent. However, this solution yields a lower value of steady-state utility. In this respect it should be mentioned that if the announced policy is credible due to commitment or reputational forces, the time-inconsistent policy can be chosen and there is a Pareto improvement of steady-state utility. Consequently, the credibility of the government's policy can play an important role in the effectivity of its policy. In this paper we deal with the two possible solutions mentioned above and present an example, which shows the importance of agreement and consistency in economic theory. Furthermore, we show that the importance of credibility increases if there are few firms in the economy. So, if we want to go into the real insights of the problem of time-inconsistency we have to analyse decentralized economies.

In future work, there are many avenues to explore. Firstly, other tax instruments, like wage or sales taxes, can be analysed. Secondly, we can investigate what will happen under the assumption of perfect competition in the labour market. Thirdly, a thorough analysis of reputational equilibria is required (e.g. Kreps and Wilson (1982)). Fourthly, it is important to perform an empirical investigation to establisch in 'which' regime the economy has been at various times. For a first and interesting attempt see Weber (1988). Finally, the framework can be used to characterize the dynamic effects of shocks or policies.

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APPENDIX 1. THE TOTAL MACRO-ECONOMIC MODEL

Given the financing scheme that the firm finances replacement investment by retained earnings and net investment by issuing new bonds.

$$q:\ \dot{q} = (r+\delta)q-a(1-\tau),\ q(\infty)=q^{*}, \tag{A1}$$

$$k:\ \dot{k} = \Phi(q)-\delta k,\ k(0)=k_{0}, \tag{A2}$$

$$x:\ \dot{x} = (\beta-r)x,\ x(\infty)=x^{*}, \tag{A3}$$

$$b:\ \dot{b} = i+\varphi(i)-\delta k-\varphi(\delta k),\ b(0)=b_{0}, \tag{A4}$$

$$\nu:\ \dot{\nu} = \beta\nu-(r+\delta)\nu-\lambda\Phi'(q)+\frac{\alpha}{c}q\Phi'(q),\ \nu(0)=0, \tag{A5}$$

$$\lambda:\ \dot{\lambda}=(\beta+\delta)\lambda-\frac{1-\alpha}{k}-(a(1-\tau)+wh)\frac{\alpha}{c},\ \lambda(\infty)=\lambda^{*}, \tag{A6}$$

$$c:\ xc = \alpha, \tag{A7}$$

$$g:\ \frac{g}{c} = \frac{1-\alpha}{\alpha}(1+\frac{\nu g}{k(1-\alpha)}), \tag{A8}$$

$$i:\ i=\Phi(q), \tag{A9}$$

$$\tau:\ g = \tau ak, \tag{A10}$$

$$l:\ l = hk, \tag{A11}$$

$$r:\ f(k,l) = c+g+i+\varphi(i) \tag{A12}$$

$$\pi:\ \pi = (f(k,l)-wl)(1-\tau)-\delta k-\varphi(\delta k)-rb \tag{A13}$$

APPENDIX 2. THE DERIVATION OF THE FBS-EQUILIBRIUM WITH ONE FIRM

As already stated before the consumers' problem can be solved independently of the government's and the firm's problem. In the feedback equilibrium the following Hamiltonian-Jacobi-Bellman equations holds for the government and the firm

$$\beta V_1-V_{1t}= \max_{\tau} \{\alpha \ln((1-\tau)ak+whk-i(t,\tau,k)-\varphi(i(t,\tau,k))) + (1-\alpha)\ln(\tau ak) + V_{1k}(i(t,\tau,k)-\delta k)\}, \tag{A14}$$

$$rV_2-V_{2t}= \max_{i} \{(1-\tau(t,k))ak-i-\varphi(i)+V_{2k}(i-\delta k)\}, \tag{A15}$$

where V_1 and V_2 are the government's and firm's value function.

From (A15) we can derive the firm's optimal level of investment

$$-1-\varphi'+V_{2k}=0 \rightarrow i = \Phi(V_{2k}),\ \Phi'=1/\varphi'',\ \Phi(1)=0. \tag{A16}$$

It is important to notice that the optimal choice of the firm's investment rate does not depend on the government's tax rate. So, the feedback Stackelberg and Nash solutions coincide (see also Başar, Haurie, Ricci (1985, p. 113)). So, it is sufficient to derive the Feedback Nash equilibria. To do so we use the method originally introduced by Starr and Ho (1969). They write down the same Hamiltonian system as in the open-loop case, but in the feedback case the instruments are not only a function of time, but also a function of state (capital). Because of that the costate-equations may be different from the open-loop case. They show also in that paper that for the Nash game this method yields the same solution as using the HJB-equations. The Hamiltonians are:

$$H_1= \alpha\ln((1-\tau)ak+whk-i(t,k)-\varphi(i(t,k))+(1-\alpha)\ln(\tau ak) +$$

$$\lambda(i(t,k)-\delta k), \tag{A17}$$

$$H_2=(1-\tau(t,k))ak-i-\varphi(i)+q(i-\delta k), \tag{A18}$$

with maximising conditions:

$$\dot{q} = rq - \frac{\partial H_2}{\partial k} = rq - \frac{\partial H_2(t,k,i,\tau)}{\partial k} - \frac{\partial H_2}{\partial \tau}.\frac{\partial \tau}{\partial k}$$

$$= (r+\delta)q-a(1-\tau)+ak\frac{\partial \tau}{\partial k}, \tag{A19}$$

$$\dot{\lambda} = \beta\lambda - \frac{\partial H_1}{\partial k} = \beta\lambda - \frac{\partial H_1(t,k,i,\tau)}{\partial k} - \frac{\partial H_1}{\partial i}.\frac{\partial i}{\partial k}$$

$$= (\beta+\delta)\lambda-\frac{\alpha}{c}(a(1-\tau)+wh)-\frac{1-\alpha}{g}, \tag{A20}$$

$$i = \Phi(q), \tag{A21}$$

$$g/c = (1-\alpha)/\alpha \longrightarrow \tau = \frac{(1-\alpha)(ak+whk-i-\varphi(i))}{ak}. \tag{A22}$$

From (A22) the derivative of τ with respect to k can be obtained. Substituting this back into equation (A19) gives us the solution. It should be noticed that this solution is different from the open-loop Nash solution, because of the last term in equation (A19). In some special differential games this last term disappears (see for example Van der Ploeg (1987)). In general this is not the case.

APPENDIX 3. THE DERIVATION OF THE FBS-EQUILIBRIUM WITH MANY FIRMS

Assume now contrary to appendix 1 that there is not one firm, but there are many firms which all have the same initial value of capital stock. Furthermore, assume that

$$k = \sum_{j=1}^{N} k_j,\ i = \sum_{j=1}^{N} i_j,\ \varphi = \sum_{j=1}^{N} \hat{\varphi}_j, \tag{A23}$$

where N is the number of firms. As is well-known in the literature there are some problems by aggregation over a large number of firms, if we work for the individual firm with the adjustment costs function as described in equation (41). There would be no problems if we use a homogeneous adjustment costs function (cf. Hayashi (1982)). However, assume for this moment that every individual firm has such an adjustment costs function that its investment is 1/N times aggregate investment, i.e. $\hat{\varphi}=\frac{1}{N}\eta i^2$.

With the same arguments as above we can show that the feedback Stackelberg and Nash equilibrium coincide. So, we can write down the following N+1-Hamiltonians:

$$H_1 = \alpha \ln((1-\tau)ak+whk-i(t,k)-\hat{\varphi}(i(t,k))+(1-\alpha)\ln(\tau ak) +$$

$$\lambda(i(t,k)-\delta k), \tag{A24}$$

$$H_{j+1} = (1-\tau(t,k))ak_j - i_j - \hat{\varphi}(i_j) + q(i_j - \delta k_j),\ j=1,\dots,N, \tag{A25}$$

with necessary conditions

$$\dot{q} = (r+\delta)q - a(1-\tau) + ak_j\frac{\partial\tau}{\partial k_j},\ j=1,\dots,N, \tag{A26}$$

$$\dot{\lambda} = (\beta+\delta)\lambda-\frac{\alpha}{c}(a(1-\tau)+wh)-\frac{1-\alpha}{g}, \tag{A27}$$

$$i_j = \frac{1}{N}\Phi(q), \ j=1,\ldots,N, \tag{A28}$$

$$g/c = (1-\alpha)/\alpha \ \rightarrow \tau = \frac{(1-\alpha)(ak+whk-i-\varphi(i))}{ak}. \tag{A29}$$

Notice that due to the fact that all firms have equal capital stocks the shadow price is equal for all firms. The crucial point is now that since the number of firms is large, the term $k_j\frac{\partial\tau}{\partial k_j} = \tau\frac{k_j}{k}\cdot\frac{\partial\tau}{\partial k}\cdot\frac{k}{\tau}$ is almost zero and equation (A26) becomes equal to (7). To be precize, k_j/k goes to zero if N increases while $\frac{\partial\tau}{\partial k}\cdot\frac{k}{\tau} = \frac{i+\varphi(i)}{y-i-\varphi(i)}$ is a constant. It should be noticed that we assume that if the number of firms increases in this economy the amount of total capital remains constant. So for the behaviour of the firms it makes no difference if there is an open-loop or a feedback information structures. This point is also recognized by Cohen and Michel (1988).

TABLE 1

A comparison of the open-loop and feedback equilbria

FEEDBACK STACKELBERG *1 firm*		FEEDBACK STACKELBERG *many firms*		OPEN-LOOP STACKELBERG
NO BINDING CONTRACTS		NO BINDING CONTRACTS		BINDING CONTRACTS
TIME-CONSISTENT		TIME-CONSISTENT		TIME-INCONSISTENT
$\frac{g^*}{c^*} = \frac{1-\alpha}{\alpha}$		$\frac{g^*}{c^*} = \frac{1-\alpha}{\alpha}$		$\frac{g^*}{c^*} = \frac{1-\alpha}{\alpha}\left(1 + \frac{\nu^* g^*}{k^* (1-\alpha)}\right)$
τ^*_{fbs}	$>$	τ^*_{fbs}	$>$	τ^*_{ols}
k^*_{fbs}	$<$	k^*_{fbs}	$<$	k^*_{ols}
u^*_{fbs}	$<$	u^*_{fbs}	$<$	u^*_{ols}

TABLE 2

A numerical example

FEEDBACK STACKELBERG *1 firm*	FEEDBACK STACKELBERG *many firms*	OPEN-LOOP STACKELBERG
$\tau^* = 0.495$	$\tau^* = 0.492$	$\tau^* = 0.135$
$q^* = 3.173$	$q^* = 3.451$	$q^* = 5.879$
$\lambda^* = 0.309$	$\lambda^* = 0.276$	$\lambda^* = 0.143$
$k^* = 43.46$	$k^* = 49.02$	$k^* = 97.59$
$c^* = 46.80$	$c^* = 52.52$	$c^* = 117.60$
$g^* = 11.70$	$g^* = 13.13$	$g^* = 7.18$
$i^* = 2.173$	$i^* = 2.451$	$i^* = 4.879$
$\varphi(i^*) = 2.361$	$\varphi(i^*) = 3.004$	$\varphi(i^*) = 11.90$
$f(k^*, l^*) = 63.04$	$f(k^*, l^*) = 71.11$	$f(k^*, l^*) = 141.6$
$u^* = 35.47$	$u^* = 39.80$	$u^* = 67.22$
$g^*/c^* = 0.250$	$g^*/c^* = 0.250$	$g^*/c^* = 0.061$

TABLE 3

The dynamic paths from feedback steady-state (FBS) to open-loop steady-state (OLS)

	k/δ	i	$\varphi(i)$	τ	c	g	$f(k,l)$	u
FBS	0.1327	0.1327	0.0110	0.4711	0.8569	0.2142	1.2126	0.6494
0	0.1327	0.1746	0.0152	0.4498	0.8182	0.2045	1.2126	0.6201
1	0.1366	0.2363	0.0279	0.2212	0.8802	0.1035	1.2479	0.5736
5	0.1626	0.3107	0.0483	0.0927	1.0748	0.0517	1.4854	0.5857
10	0.2029	0.3751	0.0704	0.0690	1.3603	0.0480	1.8537	0.6967
50	0.5762	0.7370	0.2716	0.0719	4.1143	0.1420	5.2649	2.0986
100	0.8377	0.8959	0.4013	0.0830	6.1188	0.2383	7.6543	3.1972
200	0.9450	0.9490	0.4503	0.0873	6.9536	0.2825	8.6354	3.6642
OLS	0.9492	0.9492	0.4505	0.0899	6.9810	0.2923	8.6730	3.7010

	l	g/c	r	λ	k	ν	q
FBS	0.7578	0.2500	0.0300	5.3320	2.6540	0.0000	1.1330
0	0.7578	0.2500	0.1303	3.9576	2.6540	0.0000	1.1746
1	0.7799	0.1176	0.0859	3.8150	2.7313	-2.6012	1.2363
5	0.9284	0.0481	0.0791	3.2446	3.2512	-9.8399	1.3107
10	1.1586	0.0353	0.0750	2.6806	4.0574	-14.1605	1.3751
50	3.2906	0.0345	0.0448	1.1380	11.5236	-13.5580	1.7370
100	4.7839	0.0390	0.0337	0.8434	16.7534	-11.4494	1.8959
200	5.3971	0.0406	0.0302	0.7641	18.9009	-10.7891	1.9490
OLS	5.4210	0.0418	0.0300	0.7641	18.9800	-10.8100	1.9490

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